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Project META (Microwave Energy Transmission for Aircraft)

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14. ABSTRACT:
The the viability of using microwave energy transmission technology to power air vehicles remotely was investigated. On-board antennas (rectennas) harvest the remotely beamed energy and transform it to a useful form of mechanical energy in order to keep the vehicle aloft for extended periods of time. While the idea of remote power transmission has been studied over the past few decades, the challenge with powering air vehicles lies in their unique geometry and dynamic flight patterns, which do not necessarily lend themselves well to power transmission.
This research effort designed and built a rectenna to receive microwave energy and convert it to usable DC power. A prototype was designed and experimentally tested under controlled conditions. The efficiency of conversion and storage was also examined.

15. SUBJECT TERMS
Microwave energy transmission, energy harvesting, remote energy, beamed energy, beaming energy, remotely powered aircraft, rectenna, microwave propulsion

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Introduction

Unmanned Aerial Vehicles, or UAVs, are used in many applications to gather intelligence without risking human lives. These aircraft, however, have limited flight time because of their reconnaissance payload requirements coupled with their limited scale. A microwave powered flight vehicle would be able to perform a reconnaissance mission continuously. Using beamed microwave energy from a remote source on the ground, the airplane gathers energy using on-board antennas. A rectifying antenna, or rectenna, harvests power and rectifies it into a form usable by an on-board electric motor that drives the propeller, providing thrust. Using a rectenna array affixed to the underside of the aircraft, the power needed to maintain flight can be remotely transmitted.

The idea of a fuel-less flight vehicle, or an aircraft that does not carry its own fuel, has been pursued in few different forms over the past decades. There are many different approaches for how to power these vehicles; however, the common theme is power must be transmitted from a source remote to the aircraft. Some of the possibilities for power transmission include solar power, the heating of air underneath the aircraft to cause thrust, and using antennas to convert microwave radiation into electrical power.

The goal of this research effort is to design and build a rectenna to receive microwave energy and convert it to usable DC power for propulsion. This requires a flexible substrate in order to conform to the aircraft exterior, and an efficient antenna design, both with respect to power and with respect to area and mass required. To this end, a prototype rectenna has been designed and experimentally tested under controlled microwave radiation. The efficiency of power conversion and storage has been characterized for this system.

Design Background

A patch antenna design has been chosen for the antenna array in order to simplify the design and manufacturing. Other designs considered include dipole antennas with discrete filter elements and dipole antennas with microstrip filter elements. The dipole antenna with filter elements is simple to manufacture but is highly polarized and thus sensitive to the orientation of incoming radiation. Microstrip filter elements have proven to be difficult to design with the constraints on manufacturing capability. Traditional PCB manufacturing techniques have a minimum line/space width of 0.006 inches; this constraint sets the minimum spacing for an interdigital capacitor design. Following the filter guidelines given in [1], the capacitor design would be a significant fraction of the antenna surface area and would likely substantially interfere with efficient operation. The remaining design option, patch antennas, has proven simpler to design.

Design Methodology

The basic patch design utilizes a square antenna sized to match the frequency and reflective plane spacing. The basic square patch antenna side should be a half wavelength, which can be calculated by equation 1. This does not take into account the fringing that occurs when the patch is placed over the conductive reflecting plane. The fringing effect can be calculated using equations 2 and 3 and is depicted in Figure 1 (all figures appear in the appendix). Since the patch is constrained to be square, the equations must be solved simultaneously in order to find a solution. The included Matlab code (see appendix) is used to solve the equations for the ideal patch dimensions. The Matlab program uses the microwave frequency, gap dimensions, dielectric constants of the materials, and various physical constants to determine the ideal patch antenna dimensions.

$$L_0 = W_0 = \frac{1}{2f\sqrt{\mu\varepsilon_r}} = \frac{c}{2f} \tag{1}$$

$$\Delta L = 0.412 * h * \frac{\left(\varepsilon_{eff} + 0.3\right)\left(\frac{W}{h} + 0.264\right)}{\left(\varepsilon_{eff} - 0.258\right)\left(\frac{W}{h} + 0.813\right)} \tag{2}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 12\left(\frac{h}{W}\right)\right)^{-1/2} \tag{3}$$

For a PCB made of FR4 that is 0.031” thick with an air gap of 0.125”, the ideal patch antenna dimensions based off the previous equations is 7.34mm. A summary of some configurations is in Table 1. The prototype board is manufactured with antennas with a 7.3mm side length. The ideal spacing of each of the elements is estimated as a half wavelength, so each antenna element is 7.3mm away from its neighboring elements.

A low pass filter has been designed and placed between each of the antenna elements to try to improve its power conversion efficiency by eliminating higher harmonics. A schematic of the antenna arrangement and the low-pass filter is in Figure 2. The filter is designed to prevent the high frequency signal from the microwave from propagating to the next element and potentially becoming out of

phase. If the signal is out of phase it can decrease the efficiency of the element through destructive interference and cause a decrease in power output. By putting a low pass filter in, the voltage experienced at the next element should be relatively constant. The filter consists of two surface mount parts — a 2.7nH chip inductor, and a 100pF chip capacitor, arranged as a typical LC low pass filer. Avago Technologies HSMS-8101 Surface Mount Microwave Schottky Mixer Diodes are utilized for each of the rectifying elements. They are designed for use in the X/Ku band, which is 10-14GHz. Since the transmitter used for testing uses a frequency of 10.5GHz, this diode matched perfectly. The diode has a maximum 350mV forward voltage loss at 1mA. This allows the diode to conduct even when there is a minimal voltage potential created by the antenna elements.

Table 1 - Example Antenna Configurations

Substrate	**Frequency**	**Reflecting Plane Distance**	**Patch Width**
Polyimide	10.5GHz	5.08×10^{-2} mm (0.002in)	7.693 mm
Polyimide	5.8GHz	5.08×10^{-2} mm (0.002in)	13.967 mm
Polyimide	2.4GHz	5.08×10^{-2} mm (0.002in)	33.823 mm
FR4	10.5GHz	1.5748 mm (0.062in)	5.627 mm
FR4	5.8GHz	1.5748 mm (0.062in)	11.2 mm
FR4	2.4GHz	1.5748 mm (0.062in)	29.0194 mm
FR4	10.5GHz	0.7874 mm (0.031in)	6.2566 mm
FR4	5.8GHz	0.7874 mm (0.031in)	11.8855 mm
FR4	2.4GHz	0.7874 mm (0.031in)	29.741 mm
FR4 + 0.125in air gap	10.5GHz	3.9624 mm (0.156in)	7.3381 mm
FR4 + 0.125in air gap	5.8GHz	3.9624 mm (0.156in)	15.9839 mm
FR4 + 0.125in air gap	2.4GHz	3.9624 mm (0.156in)	44.3524 mm

The antenna layout is designed to successfully integrate the parts. The antenna feed points are chosen just to allow straight connections between the patch elements. The traces are sized to match the component pads and are kept as short as possible to minimize pickup and re-radiation.

Antenna Prototype

The completed prototype is approximately three by four inches and contains thirty-five patch antenna elements in an array of five elements in series paralleled as seven strings. The board layout is in Figure 3, with a picture of an assembled array in Figure 4. A previous design is shown in Figure 5; it was discarded because the effect of the curved traces, multiple diodes, and feed point positioning was suboptimal and contributed to poor operation. The prototype was tested using a 10.5GHz, 15mW microwave transmitter (Figure 6) on loan from the Department of Physics at Cornell. (The transmitter was originally used to demonstrate various electromagnetic wave behaviors.) The transmitter has been fitted with a horn in order to increase the focus and directionality of the emitted radiation. Included with the antenna is a receiver that uses a panel meter to display relative power received. By adjusting the gain on the receiver to read 100% without the antenna in the beam path, the power absorbed by the antenna array can be estimated. This, combined with the power output from the antenna array, and the specified 15mW output from the transmitter provides an estimate of the efficiency.

Results and Discussion

The prototype antenna successfully receives and rectifies 10.5GHz microwaves for immediate use for powering DC devices or storage for later use. The output power from the antenna array has been measured up to 9mW with an appropriately placed reflecting plane. Without a reflecting plane, the power output is reduced by approximately 50%. This seems to correspond well with theory and the reason for a reflecting plane. With a 9mW power output, the power density is 1.16 W/m^2 ($116\mu W/cm^2$). This seems reasonable for the simple antenna design and the transmitter. When the antenna is placed in front of the receiver, the power meter drops to between 50 and 60% of the original value. This, combined with the specified power output of 15mW, and the received power of approximately 8mW under typical conditions leads to approximately 50% efficiency of the antenna. Of the microwave energy that is irradiant, approximately half of the power is converted into usable DC energy. A plot of the measured voltage difference across each of the antenna elements while the antenna is loaded by a 4700Ω resistor is in Figure 8. This shows how the output power of the emitter varies as it passes through the plane of the antenna.

Since the antenna uses a single diode it will rectify only half of the waveform. This inherently causes half of the power to be unusable. Adding additional diodes might allow for higher power conversion efficiency. Placing additional diodes might also allow multiple polarities to be rectified, decreasing the need for precise antenna alignment and transmission.

A resistive load is placed across the antenna to measure the power output. A capacitor is placed in parallel with the load in order to smooth the power output from the antenna. The transmitter pulses at 60Hz, which means the antenna only produces short bursts of output at 60Hz. A plot of the antenna output is in Figure 7. By placing a capacitor across the antenna, the output is smoothed to a steady DC voltage. The resistance of the load and the voltage across the load is measured using a Fluke 117 digital

multimeter with 0.9% and 0.5% accuracy specification, respectively. The power is calculated using Ohm's law, yielding to $P = V^2/R$, where V is the measured voltage across the resistor and R is the measured resistance. This assumes that no power is lost across the capacitor. Since the capacitor has a finite leakage current, this is not a valid assumption, but it can be assumed that the leakage current is negligible compared to the current through the resistor, and so it is ignored.

By varying the resistance of the load with a potentiometer, and measuring the power output of the antenna, the impedance of the antenna can be estimated. A plot of the results is in Figure 10. From this analysis, antenna has an impedance of approximately 2500Ω. A more thorough evaluation would provide more information on the actual impedance under various conditions. As the environment surrounding an antenna changes, the performance of the antenna also varies, which means the impedance can also change.

The distance between the antenna and the emitter horn is also varied and the power output determined at various locations. A 4700Ω resistor and a 1000µF capacitor are placed in parallel across the antenna in order to provide a DC output and to provide a load for power dissipation. A plot of the results is in Figure 11. As can be seen, the power output decreases as the distance increases. This is consistent with theory of electromagnetic wave propagation. Additionally, the effect of nodes is visible, as a dip in output power is observed every one-half wavelength. Between each of the nodes, a peak in power output is observed.   This is also consistent with electromagnetic standing wave theories. Clearly, the emitter is generating the microwaves consistently, so it is producing a standing wave field. In an airborne application, the fluctuations would occur quickly, and would appear as an AC ripple in the output voltage.

Capacitors are charged from a discharged state and the power produced by the antenna monitored throughout the process. The capacitors are connected directly across the antenna with no resistors or other components. Plots of various capacitors charging are in Figure 14, Figure 15, Figure 16, and Figure 17. As can be seen, the antenna is easily capable of charging a capacitor with a significant amount of energy. For each of the experiments, there is a peak in power output shortly after the charging process begins. This peak reaches ~3mW among all the tests. The power output then begins to drop until it reaches a steady state value, likely due to leakage in the capacitor.

In order to try and capitalize on the ability for the antenna to produce a small amount of power as long as necessary, an energy storage circuit is built utilizing a low power 555 timer, Texas Instruments part TLC551. The TLC551 is capable of running with a supply voltage of only one volt with a supply current of only 15µA. With a low operating voltage and current, the timer is able to run on the power from the antenna easily. The circuit is designed to charge a capacitor then discharge it through a load, in this case, an LED. This discharge only occurs once a sufficient charge has built up across the capacitor, which means that the load can use more energy for a short period than would otherwise be available if the load were powered directly by the antenna. This can be used for intermittent data collection or other such tasks that can use power for a brief period then enter a low-power, or sleep, state. The circuit is shown in Figure 12 and a plot of the voltage across the storage capacitor versus time, showing

the charge and discharge cycles, is in Figure 13. The circuit has room for improvement, such as allowing less of the energy stored in the capacitor to be dissipated in elements other than the load.

Conclusions

The prototype antenna demonstrates that a 10.5GHz rectifying antenna is feasible for beamed energy harvesting. The antenna is versatile and can be used to power small circuits, up to several milliwatts under excellent conditions. The antenna could be made more useful by manufacturing it on a flexible substrate with an integrated reflecting plane. That would ensure that the reflecting plane was at the right distance from the antenna, and would allow the antenna to be shaped to fit the contour of an airplane wing. Additional antenna designs could allow for more reception of microwaves with varying frequency and polarization.

Further funding will permit the application of the results to experimental aircraft. Additionally, we could develop more powerful microwave sources which would permit flying vehicles to be energized via microwave power.

References

[1] Brown, W. C., "Rectenna Technology Program: Ultra Light 2.45 GHz Rectenna and 20 GHz Rectenna," NASA-CR-179558, 1987.

Appendix of Figures and MATLAB™ Code

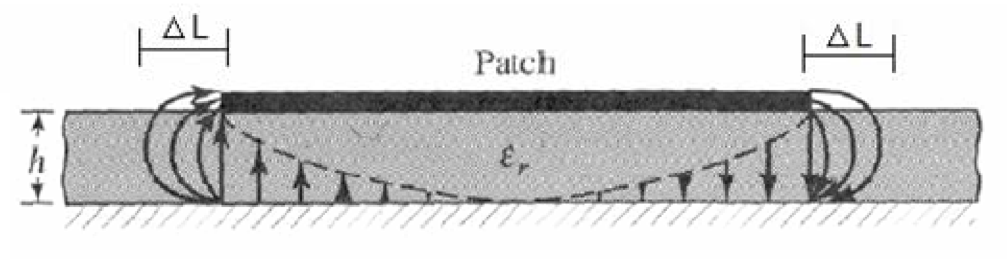

Figure 1 - Fringing Effect

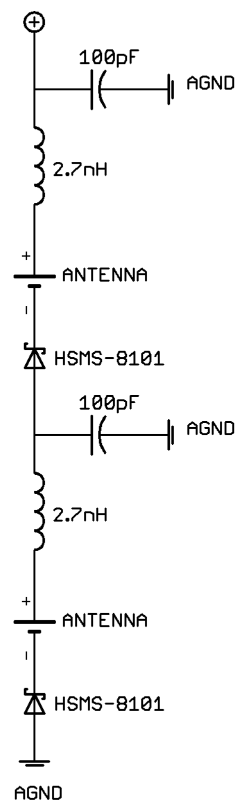

Figure 2 - Schematic of two series antenna elements

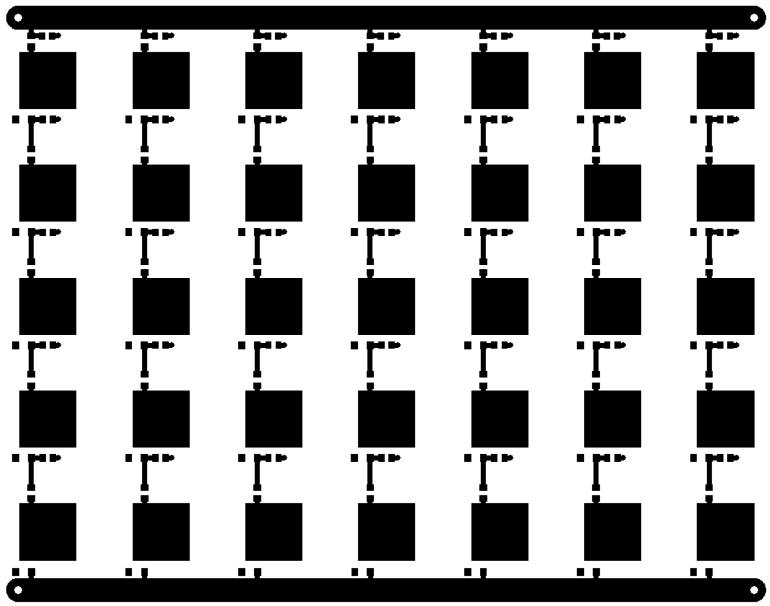

Figure 3 - Patch antenna array with associated filter components.

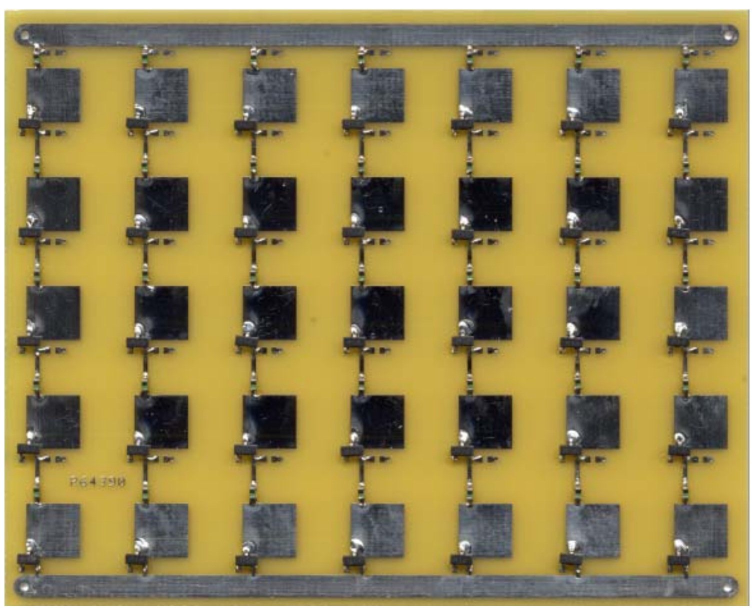

Figure 4 - Assembled Antenna Array

Figure 5 – Previously considered design

Figure 6 - 10.5GHz 15mW emitter acquired from the physics department.

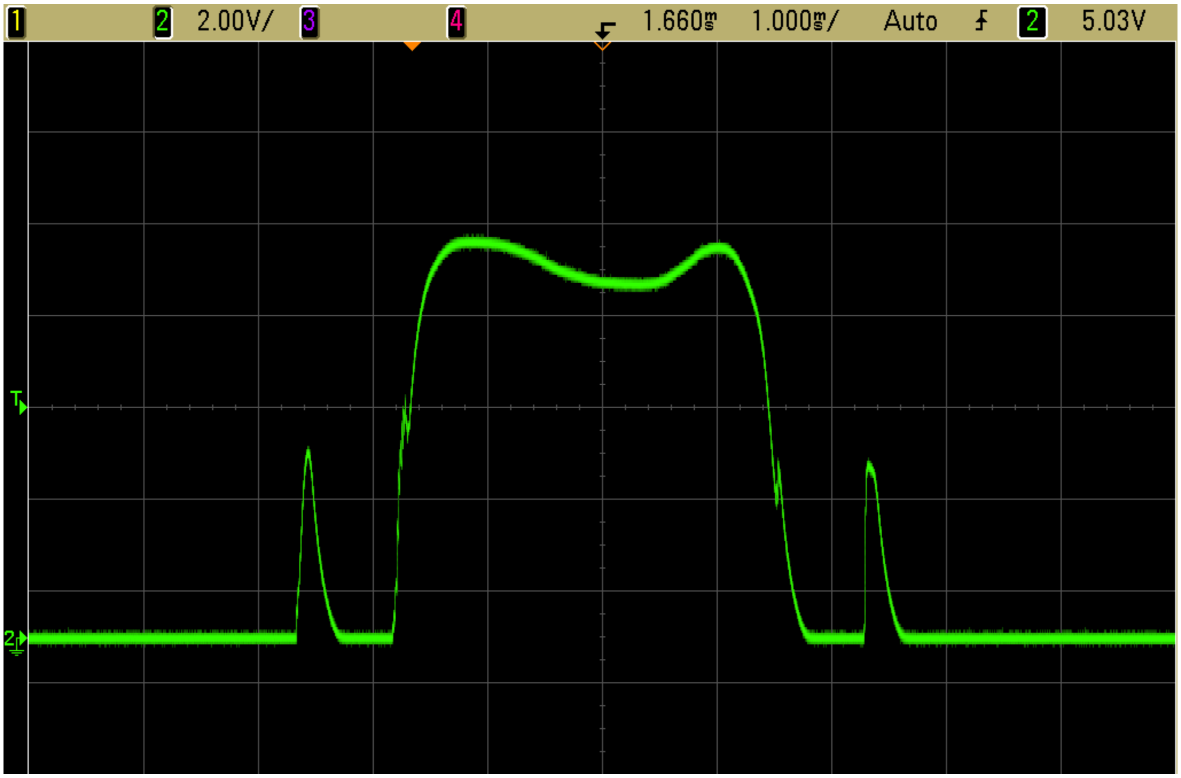

Figure 7 - Unfiltered output from antenna

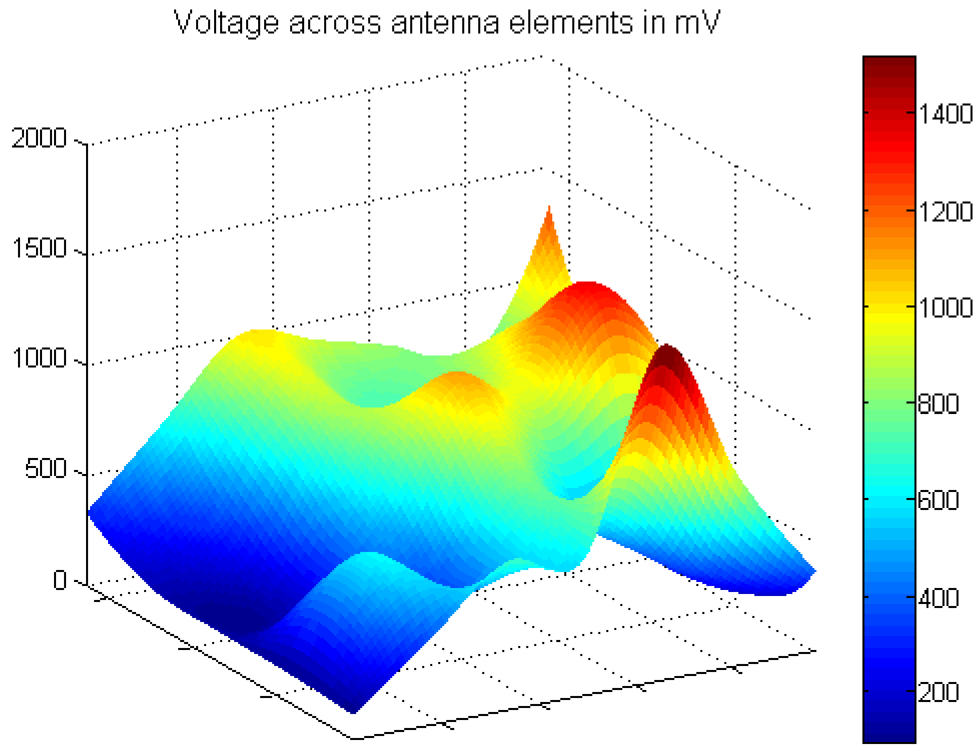

Figure 8 - Measured voltage across antenna elements

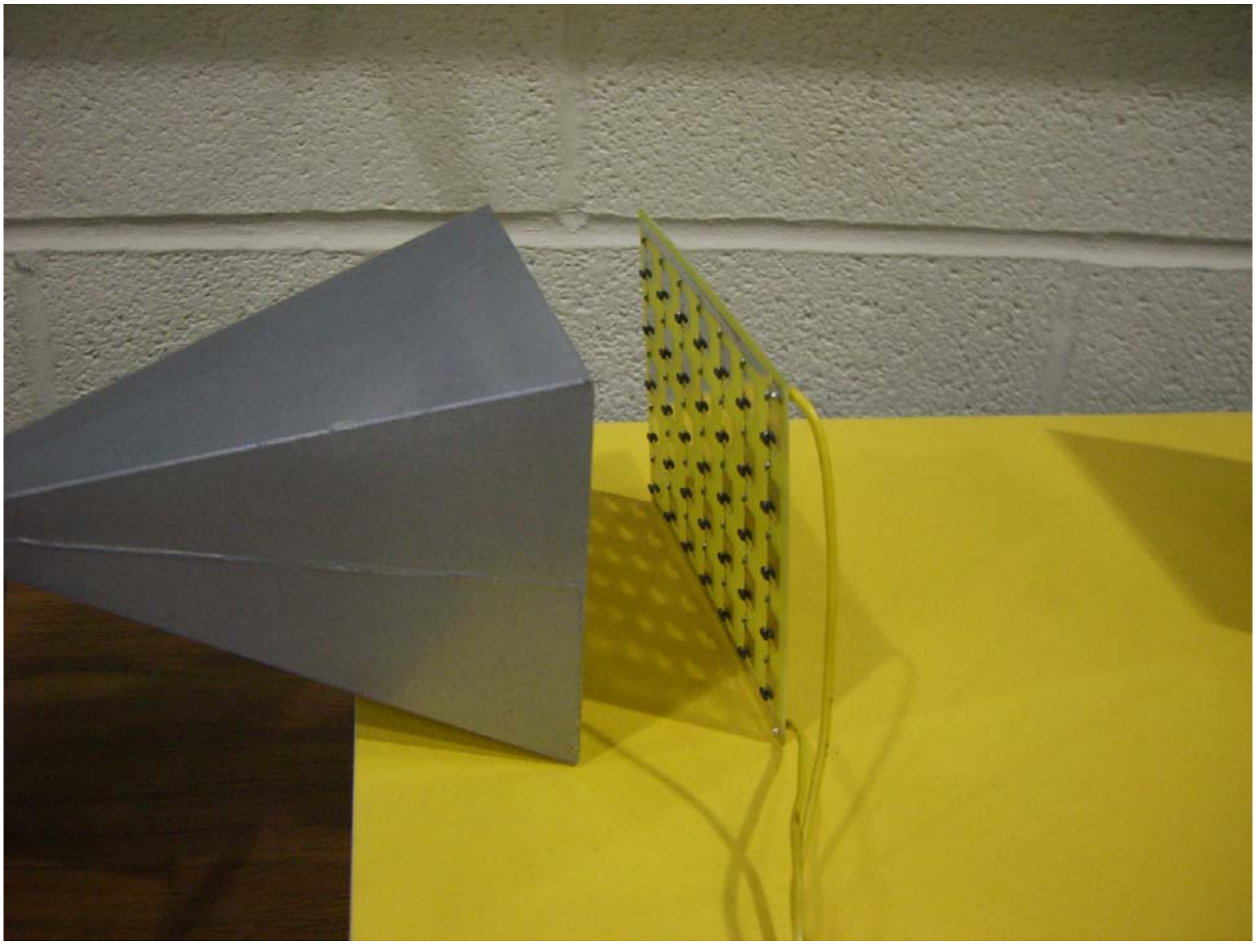

Figure 9 - Antenna under powered testing conditions

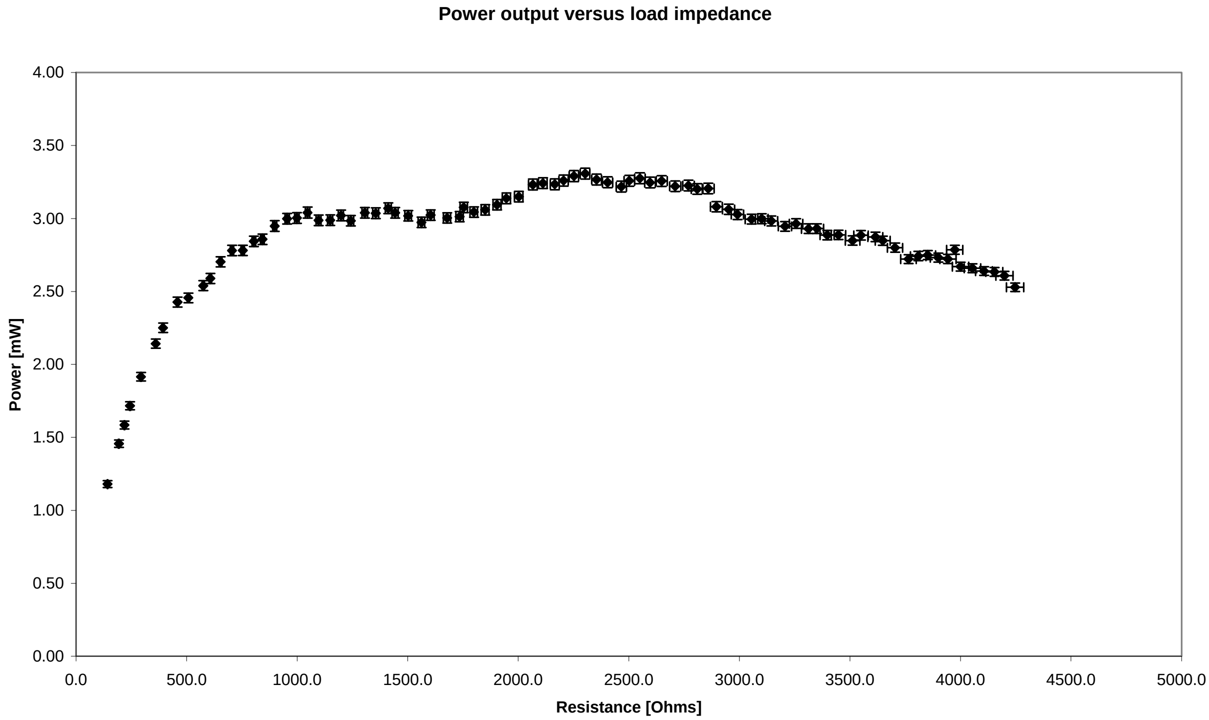

Figure 10 - Power output as the load impedance varies

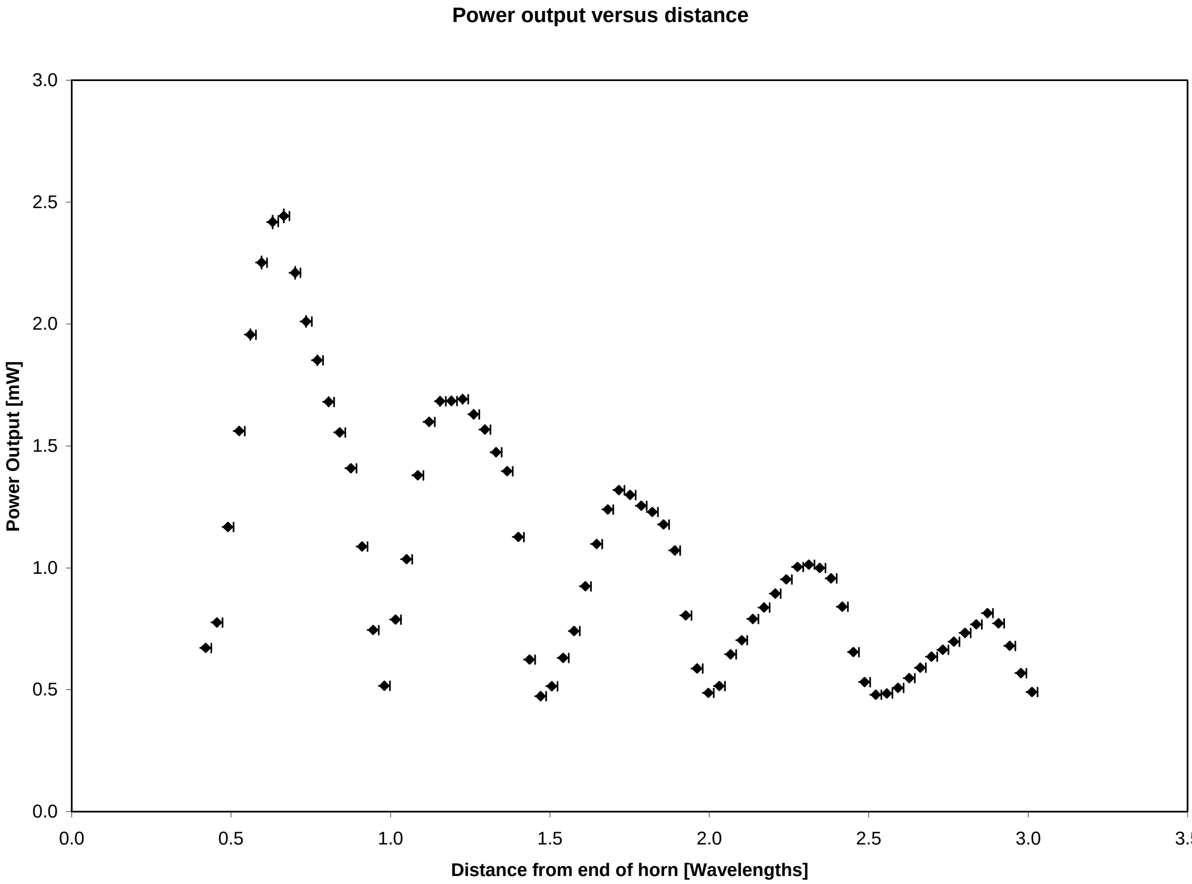

Figure 11 - Power output as the antenna varies in distance from the transmitter

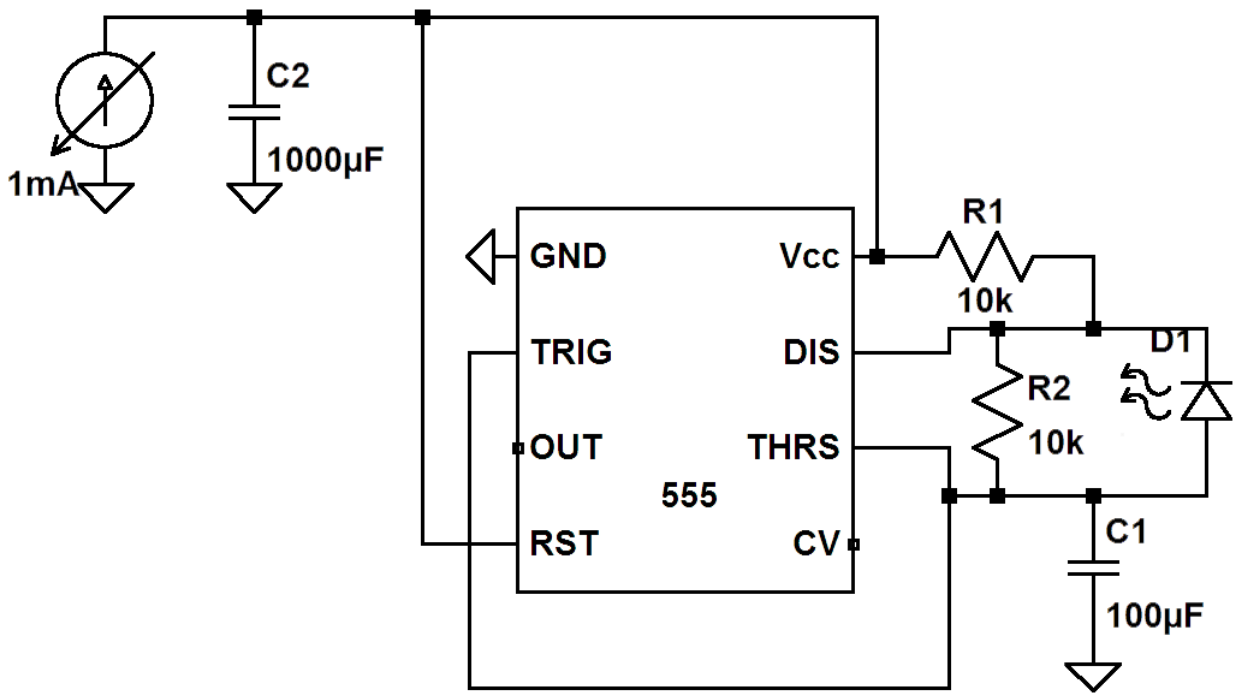

Figure 12 - Circuit utilizing 555 timer to store energy in a capacitor (C1) and dissipate it periodically through an LED (D1)

Figure 13 – Measured plot of voltage across capacitor (C1) versus time

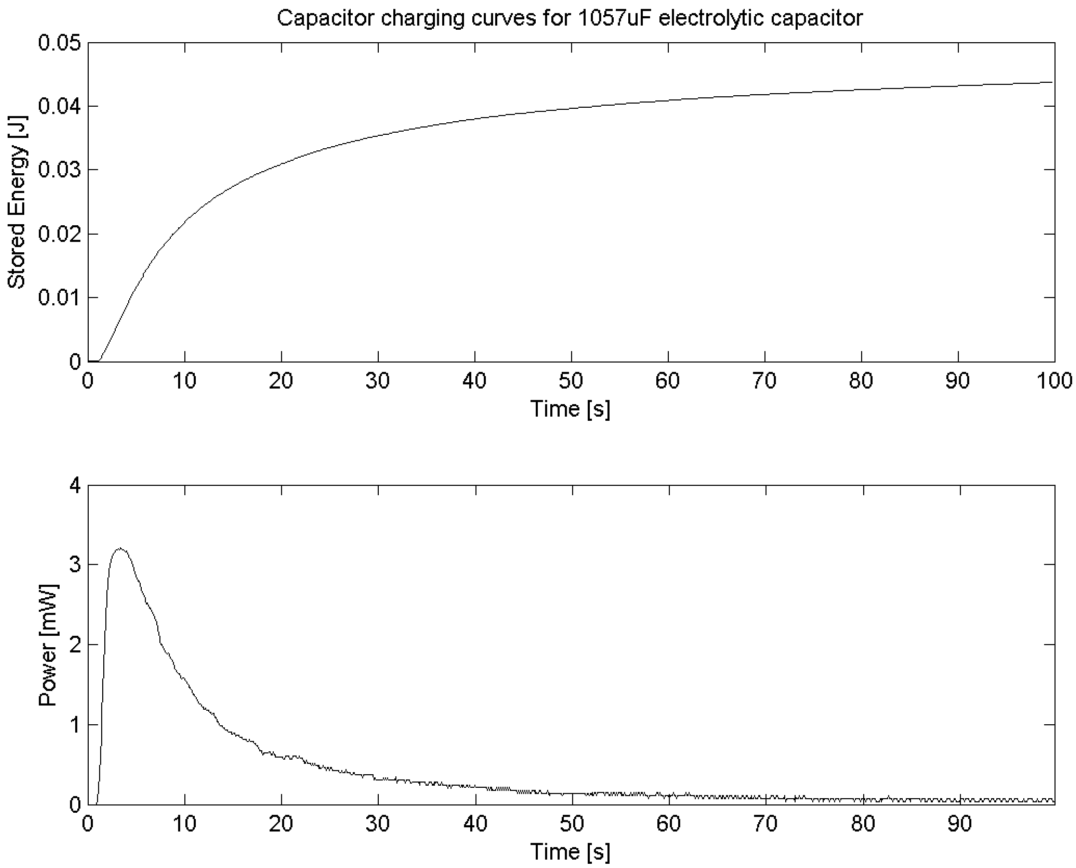

Figure 14 - Energy and power output for charging a 1000µF (measured: 1057µF) electrolytic capacitor

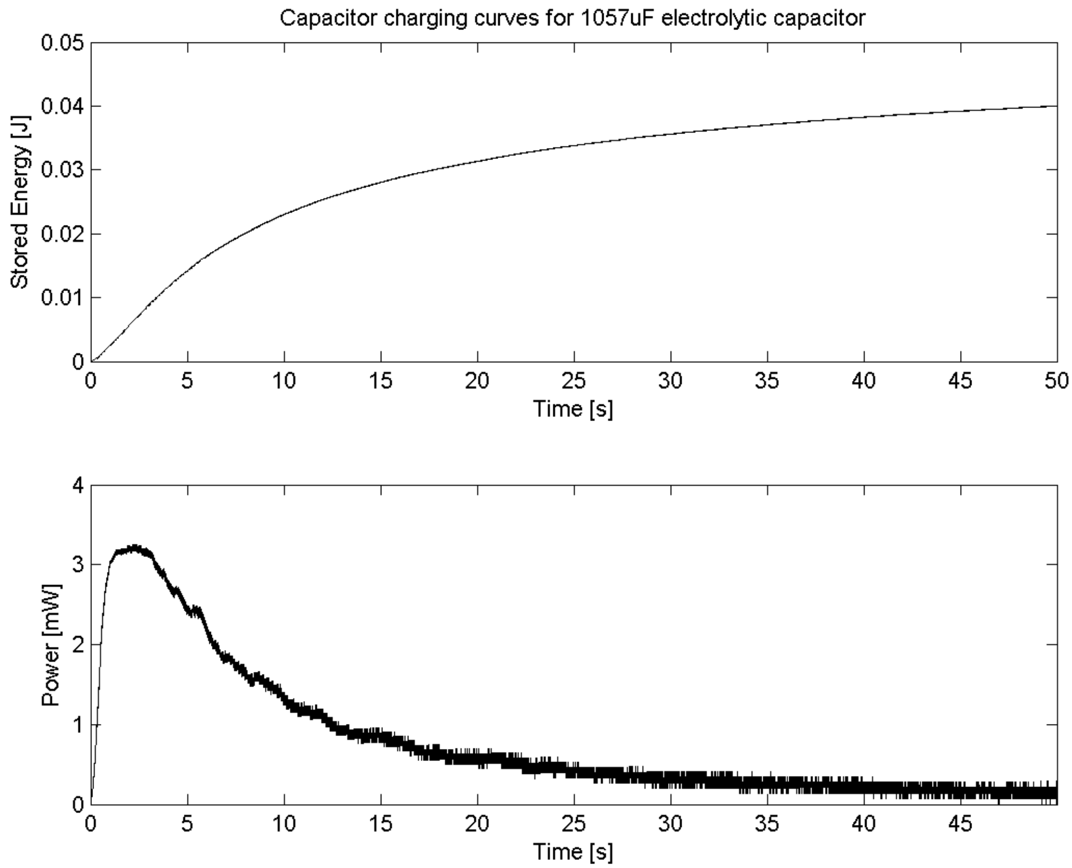

Figure 15 - Energy and power output for charging a 1000µF (measured: 1057µF) electrolytic capacitor

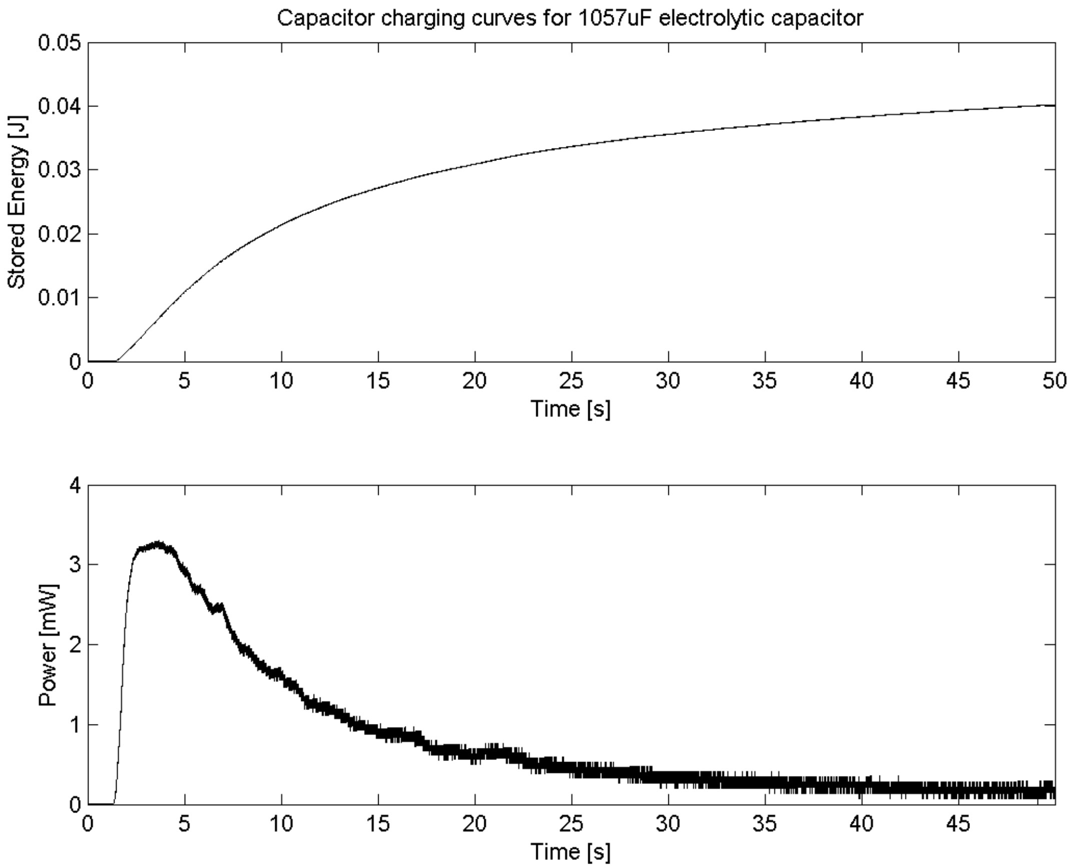

Figure 16 - Energy and power output for charging a 1000μF (measured: 1057μF) electrolytic capacitor

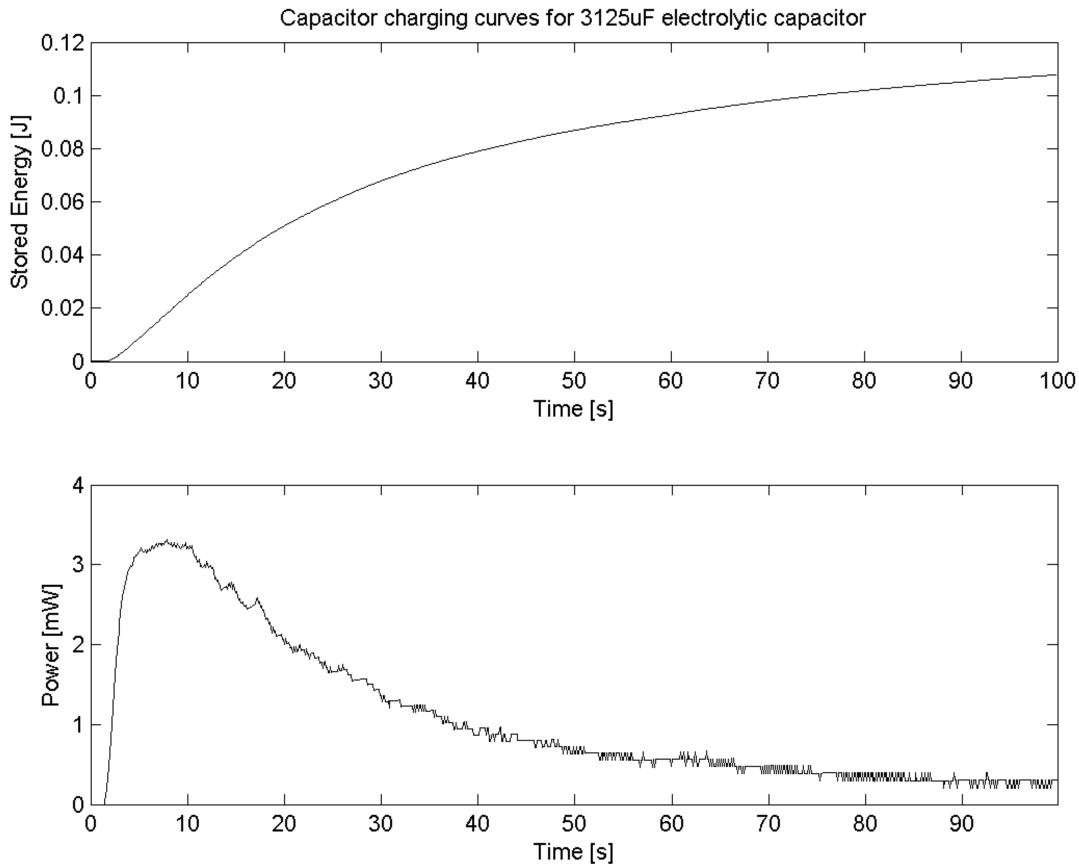

Figure 17 - Energy and power output for charging a 3300µF (measured: 3125µF) electrolytic capacitor

```matlab
function squarepatch()
%This determines the optimal side length for a square patch antenna at a
%specific frequency given by 'fc' and given a spacing specification by 'h'
%and 'er'.
clc;

fc = 10.5*(10^9); %10.5GHz center frequency
%fc = 5.8*(10^9); %5.8GHz center frequency
%fc = 2.4*(10^9); %2.4GHz center frequency

boardThickness = 0.031; %inches
AirGap = .125; %inches
h = (boardThickness+AirGap)*0.0254; %convert to m

%for flexible antenna design:
%h = (.062)*0.0254; %62 thou of FR4/adhesive between outside copper layers
%h = (.031)*0.0254; %31 thou of FR4/adhesive between outside copper layers
%h =(.002)*0.0254; %2 thou of polyimide (1 thou of polyimide and 1 thou of
adhesive)
%h =(.003)*0.0254; %3 thou of polyimide (1 thou of polyimide and 1 thou of
adhesive per side)

%calculate the weighted average of the dielectric constant for airgap case
er = ((1.00059*AirGap)+(4.2*boardThickness))/(boardThickness+AirGap);
%air+board

%er = 3.4; %foam
%er = 1.00059; %AIR
%er=3.76; %FR406 at 10GHz
%er=3.69; %IS410 at 10GHz
%er = 4.2; %FR4 dielectric constant at 10GHz
%er = 3.4; %polyimide dielectric constant
```

```
v = 4*pi()*8.854*(10^-12)*(10^-7); %premuliply constants to reduce clutter

Lo = 1/(2*fc*sqrt(v*er)); %nominal length

Wo = Lo; %square patch


%now need to take into account fringing


%check around the nominal length, doesn't change much

W = linspace(Wo*.5,Wo*1.1,100000);


%calculate the effective dielectric constant

eeff = ((er+1)./2) + ((er-1)*((1+12.*h./W).^(-.5))./2);


%calculate the change in length

dL = .412.*h.*((eeff+.3).*((W./h)+0.264))./((eeff-0.258).*((W./h)+.813));


%find the new length

L = Lo - (2.*dL);


%the length with the smallest error is the solution closest to a square

%find this solution, and present it as the final solution

Lf = L(find(abs(L-W)==min(abs(L-W))))*1000; %<-mm %/2.54; %<-inches


disp(['Patch Side Length: ' num2str(Lf) ' mm'])
```

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